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STRUCTURE OF PENETRATING ATMOSPHERIC COSMIC RAY SHOWERS

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/Table and figures are appended./

Introduction

Penetrating particles in extensive atmospheric showers were first revealed by Auger and his co-workers /1/. Hillberry /2/, Wataghin and co-workers /3/, Rogozinskiy /4/, Hillberry and Regener /5/, and others further confirmed the existence, in the air, of correlated penetrating particles of cosmic showers. Data of many research workers /6, 7/ before 1946 indicated the existence of certain separate types of showers, namely, extensive electron and photon atmospheric showers of cascade origin (possibly with a small admixture of mesons), narrow penetrating showers presumably of a meson nature, and extensive showers composed of penetrating particles possibly accompanied by soft particles.

However, the experimental material was too meager to prove the existence of two types of extensive showers, although narrow atmospheric showers apparently exist as a special well-established type of shower /7/.

Extensive showers containing penetrating particles (we shall in the future call such showers "penetrating") required more study concerning their structure, i.e., their "geometry" and composition. To this end a great many experiments were conducted in 1945 at 3,860 meters by Bell, Birger, and Veksler /8/. The equipment employed consisted of three groups of horizontal proportional counters and a proportional amplifier of triple coincidences. Measurements were taken with lead (10 centimeters) and without lead over two low groups of counters disposed one above the other.

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The results of this work may be briefly summed up as follows:

1. Distribution curves of pulse magnitudes in the proportional telescope (composed of three vertically disposed groups of proportional counters) proved to be similar when measured with lead (penetrating showers) or without lead over the respective chambers.

2. The dependence of coincidence frequency upon the distance between one of the groups of counters and the axis of the two remaining groups was identical in measurements both with 10 centimeters of lead and without lead.

3. For the most part narrow showers, measured both with and without lead, were not dense. Dense showers, however, appeared to be extensive, i.e., their number depended only slightly upon the distance between the chambers with counters.

The maximum distance in these experiments was 1.25 meters.

These results showed that soft and hard showers behaved similarly up to 1.25 meters. Thus, they indicated a genetic connection between soft and hard showers and also showed that the radius of dense penetrating showers was apparently considerably greater than one meter.

Hence, it seemed desirable to continue experiments at greater distances for further study of the structure of penetrating showers. Especially desirable were further studies of the relation between soft and penetrating showers and, as far as possible, the discovery of the nature of hard particles, which are useful in making measurements with lead.

Method of Measurement

In this work we varied the method of measurement somewhat.

The equipment employed consisted of two proportional telescopes, each composed of two groups of horizontal proportional counters, T (Figure 1). Each group of counters was composed of three counters interconnected in parallel with a total working space of 450 cubic centimeters. The distance between the chambers of the telescope was 41.5 centimeters.

The working capacity, dimensions and characteristics of the horizontal proportional counters employed did not differ from those of previously described counters [9]. From a structural standpoint, however, the two types of counters were essentially different. The counter cathodes used in this work were made of copper tubing one millimeter thick. The counters were sealed airtight by soldering small glass tubes to the ends of the cathodes instead of using ebonite corks. This considerably increased mechanical stability and resistance to temperature in the counters. Since the latter were not subjected to a special vacuum process, we introduced metallic sodium into them to keep the operating gas pure. The working volume was 25 centimeters long, 2 centimeters high and 6 centimeters wide. The counters were filled with high-purity argon up to a pressure of 74 centimeters of mercury.

High pressure was supplied separately to each of the 12 counters used in the installation, which made it possible to select and maintain the required intensification in each counter separately. The total "background" of each group (composed of three counters) was controlled on a conversion system; in case of deviation from the specified value, the background in each counter was checked separately. Further, the frequency of double coincidences in each telescope was measured continuously.

To register the pulses from the meters, two amplifiers of double coincidence, A_1 and A_2 (Figure 1) were used. Each amplifier registered the double coincidences on a separate counting machine, C_2. All four branches of the amplifiers were identical and contained the three stages of initial amplifier and a multivibrator. The latter served to create a sensitivity threshold for the system. The sensitivity of each branch was varied by varying the amplification of the system or (in cases of a small variation in sensitivity) by varying the gas pressure of the counters. Selection of the pulse coincidences from the multivibrators in each amplifier was made by the usual selective lamp method. The determining capacity of each of the amplifiers was $\tau \cong 3 \cdot 10^{-5}$ seconds. By means of a separate block, M, coincidences of double coincidences from each of the amplifiers were registered, i.e., fourfold coincidences were registered.

A method first suggested by Alikhanov, Alikhanyan, and Nikitin [10] was used to graduate the exact sensitivity of each telescope, i.e., to determine the minimum number of fast particles, n_{min}, (for a given sensitivity) that operates amplifiers of double coincidence. The frequency of double coincidence in the telescope was measured first (with 12 centimeters of lead between the chambers and 7 centimeters on each side of the lower chamber) as a function of sensitivity in the counters. The sensitivity of the counter was defined with sufficient accuracy for our purposes by its background. The curve obtained for frequency of double coincidences in the telescope versus background in the counters is shown in Figure 2 (identical grounds were selected for all counters).

Chance double coincidences, which were an important factor when the backgrounds were large, were taken into account. The plateau of the double coincidence curve thus obtained indicated that all the particles of a hard component were registered.

The fluctuation curve of ionization losses calculated by Landau [11] assured us that, when particles of given energy passed through a specific thickness of matter (in our case through the gas of the counter), only 70 percent of all particles had losses greater than the most probable loss. Thus, only 50 percent of all the particles of the hard component lost simultaneously, in both counter groups, energy greater than, or equal to, the most probable loss; consequently, the frequency of double coincidences in the telescope at the threshold corresponding to the most probable ionization of a fast particle was half the frequency of double coincidences from every hard component or, to state it differently, half the frequency of double coincidences corresponding to the plateau of the curve in Figure 2. Hence, if we take the most probable ionization of a fast particle provisionally as unity, the background in the counters corresponding to the frequency of double coincidences will be equal to half the coincidence frequency of the plateau (point U in Figure 2) and will correspond to the sensitivity of registration of one or more fast particles passing through the telescope. Now if we change the amplification by a known number of times, then the absolute sensitivity of the telescope can be determined with various counter grounds or, what is essentially the same thing, with a different frequency of double coincidences with each telescope. Let us apply the graduation method described only to the passage through the counter of particles of completely determined energy. Actually, however, because the energy spectrum of hard component particles was continuous, the graduation obtained referred to some "average" fast particle. Uniformity in the tracks of all particles in counters was the most essential need in our method of graduation. Due to the use of horizontal counters, the maximum scattering of the tracks probably did not exceed 20 percent. In fact, the scattering of the tracks influenced the accuracy of the measurements considerably less than this amount.

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Finally, in graduation by the above method, the average ionization of each of a large number of simultaneously ionizing particles must be considered considerably larger than the probable ionization of each of them separately.

Results of Measurements

All experiments were conducted in small plywood houses lined inside with felting for thermal insulation. The houses were in the open. All observations were carried out at 3,860 meters.

The arrangement of the counters is shown in Figure 1. Screened boxes with counters were placed on a wooden table one meter from the ground. For measurements made with lead, there were 12 centimeters of lead over the lower box and 7 centimeters of lead on the sides.

Special measurements were made to record the frequency of fourfold coincidences for three different sensitivities at distances D = 0.5, 2.0 and 9.0 meters between the axes of the telescopes. For one of the sensitivities corresponding to the passage of three particles, measurements were made of the frequency of fourfold coincidences with a telescopic disposition of all four counter groups. These measurements were made at the former distance between the outer boxes of counters (41.5 centimeters) and without lead. The results obtained are given in Table 1. Measurements made without lead between the chambers of the telescope are designated by Pb_0, measurements made with lead in only one of the telescopes are designated by Pb_1, and with lead in both telescopes, by Pb_2. Sensitivity is expressed as the minimum shower density ρ_{min} capable of operating the system. All errors were statistical (chance errors).

In Figure 3 the distribution curves represent the magnitude of the showers; curves measured without lead are shown as a dotted curve, and those with lead in both telescopes as an unbroken curve. (The curve for D = 2.0 meters, obtained when there was lead in both telescopes, is not shown, as it was very close to the curve for D = 0.5 meter.) After recalculation, th results in this diagram represented those obtained by Zatsepin and Eydus [12] at the same height (3,860 meters) by measuring sixfold coincidences in a system composed of Geiger "high-speed" counters, disposed in the angles of a rectilinear hexagon, with a distance between the opposite sides of 1.25 meters. The lower curve, according to these authors, was obtained by covering each of the six counters with 12-centimeter lead on top and 7-centimeter lead on the sides.

In Figure 4, the curves measured by us describe the frequency of fourfold coincidences ν_4 versus the distance D between the axes of the telescopes for three different sensitivities, and measured with and without lead in both telescopes.

The table evidently proves that all curves for lead in one telescope (Pb_1) are like the curves in Figures 3 and 4.

Discussion of Results

1. Atmospheric Showers Measured Without Lead

As may be seen from Figure 3, the distribution curves of magnitude for both hard showers (lead in both telescopes) and showers measured without lead have identical shapes for all three distances, namely 0.5, 2.0 and 9.0 meters. This fact demonstrates that coincidences were caused by the same type of shower for all these distances. Moreover, comparison with the Zatsepin-Eydus curve showed that, for showers of low density, the number of showers measured by our apparatus was considerably less than the number of showers measured by the

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Geiger counters. Actually, however, this discrepancy may be considered only apparent, since the data from the Geiger counters was calculated taking into account the fluctuations in the particle density of the shower. In our apparatus, density fluctuations, like ionization fluctuations, registered strongly and led to considerable error in counting low-density showers.

Calculations made by us actually showed that the discrepancy observed could be explained satisfactorily by fluctuations in the density and ionization of shower particles. On the other hand, when a large number of particles hit each group of counters, density fluctuations had no influence and ionization fluctuations were easily calculated (if the ratio of average ionization to the most probable ionization is known). Such a case may be treated with sufficient accuracy when nine particles fall on the counter box. In this case ($\rho \gtrsim 200\,m^{-2}$), as may be seen from Figure 3, both methods actually agreed as to their results. This indicates that the method we applied in measuring dense atmospheric showers registered precisely their particle density. Particularly, if there were heavy particles in extensive atmospheric showers, their value by our method of recording would not be great, while in the contrary case the coincidence frequency measured by our installation would considerably exceed the readings of the Geiger counter system. Even in this case the results obtained naturally did not exclude the possibility that heavy particles could be an important factor in some other experimental setup for recording showers, e.g., ionized particles undoubtedly were an important factor in Lewis' experiments [13].

Turning to Figure 4, we note the similarity of all three curves describing coincidence frequency versus distance, $\nu_4(D)$, for all three densities. Furthermore, for all three sensitivities the coincidence frequency decreased very little with distance. This fact must be especially noted in the case of low-density showers.

It was shown earlier both by us [8] and by Alikhanyan and Asatiani [14] that narrow atmospheric showers were for the most part not dense. Our results showed that the density of narrow showers of radius 0.5 to 1.0 meter must be less than about $\rho = 35m^{-2}$.

Comparison of our curve for $\nu_4(D)$ with the thoretical curve obtained from the cascade theory, which takes into consideration the scattering of shower particles, was of considerable interest (especially in connection with Lewis' experiments [13] on the study of atmospheric showers by the ionization chamber method). Calculations were made with the theoretical formulas of Belen'kiy [15], which took into consideration the ionization losses of cascade electrons. The function $\nu(D)$ was calculated by the method first applied by H. Euler [16]. The distribution function of particles was employed by us in the form

$$\rho = \rho_0 \cdot R^{-(2-s)}\, e^{-\alpha R}$$

where ρ is the shower density at distance R from the axis, ρ_0 is a parameter dependent on the energy of the primary particle, s is a parameter in the cascade theory, and α is a constant. The integral distribution (spectrum) of primary electrons was given the usual form:

$$F(E_0) = H \cdot E_0^{-1.8}$$

where H is some constant.

The theoretical curve for a shower of density $\rho \geqslant 200m^{-2}$ is not shown in Figure 4 since it agreed so well with the corresponding experimental curve. (If the theoretical curve fits the experimental curve at the point D = 0.5 meter, the usually accepted value of H must be increased

3.7 times, as was proved.) Thus the experimental results, according to Auger showers, gave an entirely satisfactory explanation of the cascade theory proceeding from the hypothesis that all scattering of shower particles is dependent exclusively on multiple Rutherford scattering.

2. Penetrating Atmospheric Showers

As may be seen from Figure 3, in the case of penetrating showers, unlike showers measured without lead, the coincidence frequency was two to three times larger than the frequency measured by a system composed of Geiger counters under lead, in spite of the fact that for low densities the fluctuations could, as previously, greatly reduce the number of showers measured by a proportional apparatus. This difference indicated that the coincidences observed under lead were probably not caused by the simple passage of fast particles through lead, but that the particles responsible for the coincidences caused the formation of penetrating particles in the lead itself.

We obtained additional proof refuting the assumption that atmospheric showers composed of penetrating particles were subject only to ionization losses in lead. Thus, such showers should cause us to expect (at least with apparatus of low sensitivity) that the number of showers measured when there was a lead compartment in one of the telescopes should equal with sufficient accuracy the number of showers measured when there was lead in both telescopes. But a lead compartment in one of the telescopes "picked out" the hard showers of a given density. As may be seen from the table, a lead compartment in the first telecope reduced the frequency of fourfold coincidences to approximately one third, but moving the lead into the second telescope caused a diminution, generally speaking, of the same order (about one half). Just such an effect should be expected of a lead plate if the formation of particles responsible for coincidences under lead proceeded with a certain probability in each layer.

Let us also note the following experiment. With a distance D = 2 meters and a sensitivity corresponding to $\rho \lesssim 70m^{-2}$, the thickness of the lead layer during the measurement of penetrating showers was increased from 12 to 16 centimeters. It was found that the coincidence frequency decreased accordingly from 2.4 ± 0.4 coincidences per hour to 1 ± 0.2 coincidences per hour, i.e., to less than half. This absorption exceeded that which might be expected for atmospheric showers composed of mesons.

As may be seen from Figure 4, the curves of coincidence frequency versus distance are quite similar for showers measured without lead and for penetrating showers. This confirmed the results [8] previously obtained and demonstrated not only that for distances up to 9.0 meters Auger showers and hard showers were not similarly distributed according to densities but also that the particles in them, in spite of differences in their penetrating ability, were identically distributed.

These facts indicated a genetic connection between soft and hard extensive atmospheric showers (at least for showers passing through 12 centimeters of lead). According to our experiments, showers composed of penetrating particles must be accompanied by a large number of softer particles.

The data adduced by us argued against assuming not only the existence of a separate atmospheric type of penetrating (meson) shower but also the presence of a considerable number of mesons in Auger showers. On the other hand, our data pointed to a genetic connection between the penetrating showers observed by us and ordinary Auger showers.

It may be thought that the electrons of Auger showers themselves pass through lead. Calculations made by us according to the cascade theory, however, argued against such a hypothesis. We have taken the cascade formulas obtained by Belen'kiy [15] as the basis of our calculations. According to him, the following formula gave the total number of particles in a shower possessing energy greater than E and moving in a direction of angle θ with the axis of the shower:

$$N(t,E,\theta) = N(t,s) \cdot F(E,\theta,s)$$

where t was the depth of the position observed, the parameter s was related to the energy E_0 of the primary particle and to the depth formula in the following manner:

$$\lambda'(s) = -\frac{1}{t}\ln\frac{E_0}{E}$$

where $\lambda'(s)$ was a tabulated function [15, 17]. When s = 1, then $F(E, \theta, s)$ has the form e^{-z}/z, where $z = E\,\theta/p$ and p is a known function of s.

The form of the function $F(E, \theta, s)$ was known to depend only slightly upon s when $1 \leqslant s \leqslant 2$ and if $E\,\theta/p \geqslant 0.7$. Inasmuch as our calculations included the essential values of s in the above interval, we could assume that

$$N(t,E,\theta) = N(t,s) \cdot e^{-\alpha\theta}/\theta$$

To pass from this angular distribution of particles to the distribution of particles according to their distance from the axes of the shower, we proceeded from the physical idea that the particles of a given energy undergo primary scattering with t considered unity. This idea was based on the cascade theory [15].

Hence, assuming that

$$N(t,E,R) = N(t,s) \cdot e^{-\alpha R}/R$$

we found N(t,s) and α from the conditions:

1) $$\frac{\int R^3 P(t,E,R)\,dR}{\int R P(t,E,R)\,dR} = \left(\frac{21}{E}\right)^2 = \overline{R}^2, \text{ where } P(t,E,R) = \frac{\partial N(t,E,R)}{\partial E}$$

2) $$\int 2\pi R N(t,E,R)\,dR = N(t,E) = \frac{H_1(s)}{s}\,\frac{e^{ys+\lambda_1(s)t}}{\sqrt{2\pi\lambda_1''(s)t}}$$

Here N(t,E) is the total number of particles at depth t for energy $\geqslant$ E; $y = \ln(E_0/E)$; λ_1, λ_1'', H_1 are tabulated functions.

Simple calculations lead to the following expression for the density of particles of energies greater than E, at a distance R from the axis of the shower:

$$\rho(t,E,R) = \frac{0.112}{2\pi}\cdot\frac{H_1(s)}{s}\cdot\frac{e^{ys+\lambda_1(s)t}}{\sqrt{2\pi\lambda_1''(s)t}}\cdot\frac{e^{-0.112ER}}{R}$$

(E is in MeV and t is in radiation units). With this formula the curve of fourfold coincidences versus scattering could be computed by the usual method [16].

In Figure 4 the upper theoretical curve was calculated on the assumption that showers containing electrons of energy $E \geqslant 10^9$ eV were registered and the density of the latter was $\rho \geqslant 200\,m^{-2}$. As may be seen from the curve, when there was lead in both telescopes, then the coincidence frequency which could be caused by high-energy electrons decreased very rapidly with distance. In fact, this decrease in the theoretical curve should be appreciably faster if it is borne in mind that, in accordance with the cascade theory, only electrons

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of energies many times greater than 10^9 eV could through 12 centimeters of lead.

The fact that there were electrons of very high energy in Auger showers which were capable, by means of cascades, of creating showers of sufficient magnitude under lead likewise could not explain the course observed for the curve $\sqrt{4}(D)$ for penetrating showers. The lower curve in Figure 4 was calculated for cascade showers containing electrons of energies $E \gg 10^{10}$ eV for a density $\rho \gg 20m^{-2}$. If we took into account that even electrons of energy 10^{10} eV were capable of creating showers composed of ten particles under 10 centimeters of lead, we should see that in this case their number decreased with increasing distance D much faster than the decrease observed. (In fact, electrons of still higher energies were needed for this purpose.)

Hence, the course of the curve could not be explained successfully by high-energy electrons in Auger showers which were subject only to the laws of cascades and which underwent only multiple Rutherford scattering.

Conclusions

1. Extensive penetrating atmospheric showers, examined under 12 centimeters of lead, did not consist of penetrating particles passing through the lead and sustaining in it only ionization losses. The particles observed under the lead absorber were generated, at least in part, by the lead.

2. There was a genetic connection between penetrating showers and ordinary Auger showers.

3. The penetrating showers observed could not be identified with showers composed of high-energy electrons, if the cascade theory in its present form correctly took into account the scattering of these electrons.

4. On the other hand, data obtained for Auger showers did not contradict the assumption that the basic particle portion of these showers was of a cascade nature.

5. To explain the results obtained for penetrating showers, the following seemed to be the most plausible possibility: when lead was used, coincidences were dependent upon the electrons or photons of ordinary Auger showers, which directly or indirectly generated in cascade the particles observed under the lead. Here, however, it was necessary to assume that, in addition to multiple Rutherford scattering, high-energy electrons were subject to scattering of another nature or that the relativistic formula for Rutherford scattering (Mott's formula) was inapplicable.

In conclusion, I take this opportunity to thank Professor V. I. Veksler for his guidance in the experimental part of this work and Doctor S. Z. Belen'kiy for his discussion of many problems.

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D(M)		0.5			2.0	
ρ_{min}	Pb_0	Pb_1	Pb_2	Pb_0	Pb_1	Pb_2
$35 m^{-2}$	18.4 ± 1.5	4.6 ± 0.4	2.0 ± 0.2	15.3 ± 1.8	5.2 ± 0.6	$2.0 \pm 0.$[illegible]
70	11.9 ± 1.0	4.5 ± 0.4	2.0 ± 0.2	9.5 ± 1.1	4.0 ± 0.5	2.4 ± 0.4
200	5.1 ± 0.5	1.6 ± 0.2	0.8 ± 0.2	4.5 ± 0.7	1.5 ± 0.3	0.9 ± 0.2

Table 1. Frequency of Fourfold Coincidences per Hour

D(M)		9.0	
ρ_{min}	Pb_0	Pb_1	Pb_2
$35 m^{-2}$	--- ---	--- ---	--- ---
70	7.2 ± 0.8	2.5 ± 0.6	1.3 ± 0.3
200	3.5 ± 0.9	1.0 ± 0.3	0.4 ± 0.2

Supplement to Table 1

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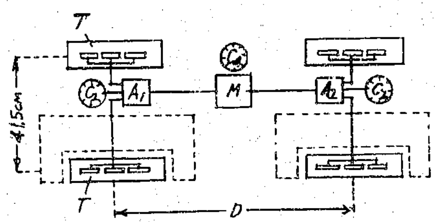

Figure 1. Schematic diagram of Equipment

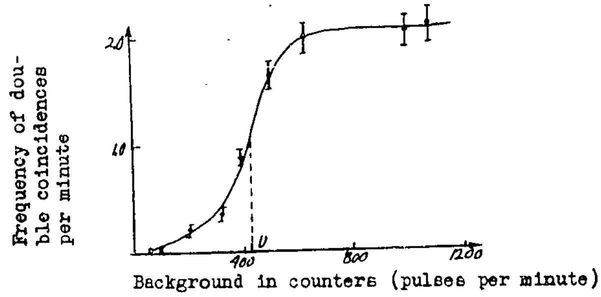

Figure 2. Frequency of Double Coincidences in Telescope versus Background in Counters with 12 centimeters of Lead Between Counter Groups

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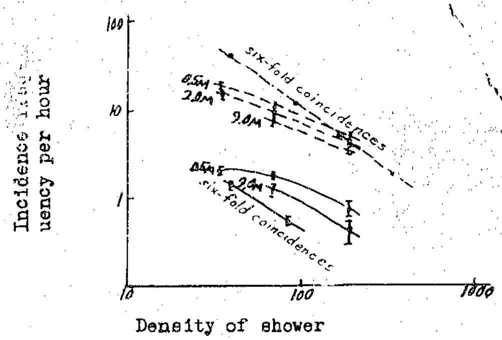

Figure 3. Distribution of Atmospheric Showers According to Magnitude.

Dotted curves are measured without lead and unbroken curves are measured with 12 centimeters lead in both telescopes.

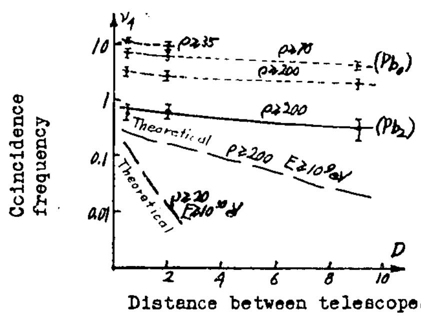

Figure 4. Frequency of Fourfold Coincidences Versus Distance Between Axes of Telescopes for Three Different Sensitivities.

Dotted curves are measurements without lead (Pb_0); unbroken curves, with lead in both telescopes (Pb_2). The lowest curves are theoretical curves; ρ is the minimum density of the recorded showers; E is the minimum energy of the shower particles under consideration.

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